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Sensitivity analysis of methodological choices in road pavement LCA

Yue Huang · Alan Spray · Tony Parry

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Abstract
Purpose There are methodological questions concerning life cycle assessment (LCA) and carbon footprint evaluation of road pavements, including allocation among co-products or at end-of-life (EOL) recycling. While the development and adoption of a standard methodology for road pavement LCA would assist in transparency and decision making, the impact of the chosen method on the results has not yet been fully explored.
Methods This paper examines the methodological choices made in UK PAS 2050 and asphalt Pavement Embodied Carbon Tool (asPECT), and reviews the allocation methods available to conduct road pavement LCA. A case study of a UK inter-urban road construction (cradle-to-laid) is presented to indicate the impact of allocation amongst co-products (bitumen and blast furnace slag); a typical UK asphalt production (cradle-to-gate) is modelled to show the influence of allocation at EOL recycling.
Results and discussion Allocation based on mass is found to consistently lead to the highest figures in all impact categories, believed to be typical for construction materials. Changing from industry chosen allocation methods (Eurobitume, asPECT) to 100 % mass or economic allocation leads to changes in results, which vary across impact categories. This study illustrates how the allocation methods for EOL recycling affect the inventory of a unit process (asphalt production).
Conclusions and recommendations Sensitivity analysis helps to understand the impact of chosen allocation method and boundary setting on LCA results. This initial work suggests that economic allocation to co-products used as secondary pavement materials may be more appropriate than mass allocation. Allocation at EOL recycling by a substitution method may remain most appropriate, even where the balance of credits between producers and users may be hampered by an inability to confidently predict future recycling rates and methods. In developing sector-specific guidelines, further sensitivity checks are recommended, such as for alternative materials and traffic management during maintenance.

Keywords Allocation · Carbon footprint · Life cycle assessment · Recycling · Road pavements · System boundary

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Y. Huang (✉) · A. Spray · T. Parry
Nottingham Transportation Engineering Centre,
University of Nottingham,
University Park,
Nottingham NG7 2RD UK
e-mail: y.huang@nottingham.ac.uk

1 Introduction

After more than 15 years of development of life cycle assessment (LCA) for road pavements (Stripple 2001; Mroueh et al. 2001; Birgisdóttir et al. 2006; Huang 2007), there are still some questions surrounding the data to use and methodological choices to make. Some belong to the ongoing development of the LCA methodology (Finkbeiner 2009), others are specific to the road sector:

- Life cycle stages
  Whether cradle-to-gate, to-laid, or to-grave, considering the complexity of the use phase and uncertainty in disposal scenarios?
- Allocation and recycling
  Which allocation procedures prescribed by ISO 14044 are appropriate to processes with multiple products/by-

products in an industry which uses many recycled or 'waste' materials? How should the benefits of recycling be credited to the producer of the primary, and the user of the recycled, material? The end-of-life (EOL) scenarios for pavement materials include reuse, recycling to lower grade, or simply left in place. Will it be practical for a pavement LCA to predict these scenarios many decades into the future?

- System boundary

  Whether to include capital goods or staff commuting for site activities, road lighting during use or vehicle fuel consumption that can be attributed to pavement properties (roughness, stiffness), and traffic delays during maintenance?
- Feedstock energy, carbon storage and land use change

  Should the feedstock energy of bitumen be counted as an energy input? How to deal with carbon sequestration by concrete exposed to air? How to include emissions caused by land use change (e.g. new construction/widening, biofuel from dedicated energy crops)?

Among the areas above, allocation and system boundary questions are considered the most significant methodological issues within the LCA community, second only to land use change (Feifel et al. 2010). While the development and adoption of a standard methodology for road pavement LCA would assist in transparency and decision making, the impact of the chosen method on the results has not yet been fully explored. The implementation of LCA in road pavements is evolving and disparate (Santero et al. 2011a). How to deal with the methodological issues above will determine the effectiveness of LCA in decision making for the road sector.

This paper examines methodological choices made by a UK specification for assessment of greenhouse gas (GHG) emissions in Section 2 and reviews allocation methods employed by the bitumen, cement and steel industry, when applied to co/by-products (in Section 3.1) and to recycling (in Section 3.2). A case study of a UK interurban road construction (cradle-to-laid) is presented in Section 4 to investigate the impact of the former; a hypothetical asphalt production (cradle-to-gate) is modelled in Section 5 to show the influence of the latter. Conclusions and recommendations are drawn in Section 6.

2 PAS 2050 and asPECT

The UK publicly available specification PAS 2050 (BSI 2011) specifies requirements for assessing the life cycle GHG emissions of goods and services, and is finding wide use in the UK, Europe and elsewhere (Sinden 2009). Clearly steered towards the harmonisation of measuring the carbon footprint of retail products, PAS 2050 includes a methodology that can also be used in other sectors, and some of the same methodological choices can be applied to conduct a full LCA. However, some methodological choices made by PAS 2050 give rise to questions of how and whether it is appropriate to apply them to road pavements:

- The exclusion of capital goods and employee transport, but inclusion of some administration activities (e.g. operation of premises)
- Where necessary, allocation among co-products on a physical (e.g. mass) or economic basis; allocation for EOL recycling (PAS 2050 Annex D) following either the 'recycled content' or 'approximation' approach that gives 100 % benefits of recycling to one party in the supply chain
- The 1 % 'materiality threshold' as a cutoff criterion needs discretionary screening prior to any analysis.
- For 'business-to-business' communication, the cradle-to-gate boundary is unable to account for the functionality of the product, such as the influence of pavement performance on vehicle fuel efficiency, or the cyclic maintenance work causing congestion and demanding future resources.
- GHG emissions due to land use change are limited to the scenarios of forest/grassland to crop land (PAS 2050 Annex C).

In 2011, UK Transport Research Laboratory, in collaboration with the Highways Agency, Mineral Products Association and Refined Bitumen Association, published the final version of the asphalt Pavement Embodied Carbon Tool (asPECT). This UK-based tool has been developed to produce PAS 2050-compliant cradle-to-grave carbon footprint reports for asphalt, except that for allocation, asPECT splits the benefits of recycling 60 %:40 % between the EOL user and original producer of recycled asphalt. The purpose is to encourage both practices in the product life cycle and meanwhile give more reward to the user in order to encourage industry recycling (Wayman et al. 2011).

3 Review of allocation methods

Allocation of environmental burdens, among co-products or at EOL recycling, has been applied in road pavement LCA, and the allocation methods are likely to be put under the spotlight when the LCA results are reviewed or challenged (Eurobitume 2011; Chen et al. 2010; Sayagh et al. 2010). This is important for materials such as bitumen from a refinery, where a variety of other petroleum products are derived, and concrete where industrial by-products are introduced to partially replace the cement. Allocation rules for EOL recycling can be defined based on whether the inherent properties of the material change as a result of recycling.

3.1 Allocation among co-products

Environmental burdens of petroleum products are advised by Wang et al. (2004) to be allocated at the 'lowest possible sub-process level' within a refinery. This involves the attribution of energy from different refinery units to intermediate product streams to develop a process-based allocation. This approach is considered by Keesom et al. (2009) to be vulnerable to lack of data on the yields and energy use at the fundamental processing level in the refinery, and the connection between process units. Eurobitume's life cycle inventory 2011 uses two methods of allocation among petroleum products including bitumen (Eurobitume 2011):

- At crude oil extraction and transport stage, where the products are treated as raw materials, the allocation is based on mass.
- At the refining stage, the allocation is based on economic value, i.e. market price of the outputs factored by their physical yields, partly because these outputs (diesel, bitumen, wax, etc.) are going to different uses.

Unlike the other two studies, the Eurobitume inventory also provides data for bitumen production taking into account capital goods (infrastructure required to produce, transport and refine crude oil). Data in some commercial LCA databases also follow this approach, such as Ecoinvent that includes the provision of roads and vehicles in the inventory of transport services by trucks (Spielmann and Scholz 2005). A sensitivity check carried out by Eurobitume indicated that the CO_2 emission of bitumen would be 22.9 % higher if allocation was 100 % by mass, or 45.0 % lower if 100 % by price (Eurobitume 2011).

A paper looking at the partial replacement of cement with ground granulated blast furnace slag (GGBS) or coal fly ash also indicated the high material embodied carbon due to mass allocation (Chen et al. 2010). Similarly, granulated blast furnace slag (BFS) used as aggregate in the base and sub-base of a road with 30-year design life increased the project CO_2-e by some 60 %, when the burdens of steel making allocated to BFS changed from 0 % (treated as waste) to 20 % (allocation by mass) (Sayagh et al. 2010).

Recycling is topical to pavement engineers. Apart from resource efficiency, some products of high embodied CO_2 can be partially replaced by outputs from other industries that are often otherwise treated as waste. For instance, US Portland Cement Association found that replacing 20 and 25 % of cement with GGBS in 20 MPa concrete will reduce CO_2 per cubic meter by 19 and 24 %, respectively; replacing 35 and 50 % of cement with fly ash in 20 MPa concrete will reduce CO_2 per cubic meter by 33 and 47 %, respectively (Marceau et al. 2007). Research in Australia indicated that CO_2-e reduction by 25 % fly ash in 20 and 25 MPa concrete is 13 and 15 %, respectively, and 40 % GGBS blended concrete show reduced CO_2-e emissions of 22 % (Flower and Sanjayan 2007). However, how the emission factors for GGBS and fly ash were calculated is not clear from the paper, although they are substantially higher than the UK figures (The Concrete Centre 2009). Case study 1, Section 4, compares co-product allocation using mass, economic and mixed methods for bitumen, and mass, economic and zero impact methods for BFS.

3.2 Allocation at end-of-life recycling

Most pavement materials are recyclable at the end of life. Complex products such as buildings and cars have different disposal scenarios for components and thus recycling is product (assembly), rather than material, based; allocation at EOL recycling in this case usually involves both the open-loop (where materials are recycled into a different product) and closed-loop (where materials are recycled into a similar product) scenarios, and is based on physical as well as economic relationships (Vogtländer et al. 2001). Products of less heterogeneous components such as road pavement mostly deal only with material-based, closed-loop recycling.

The route taken by recycling metals is worth referring to. For instance, the steel industry uses the 'substitution' method, which requires an assumption of EOL recovery rate and the ratio of steel to scrap yield (World Steel Association 2008), as shown by Eq. 1a. In this method, original production of the recyclable steel is given the full benefits of recycling at EOL. The aluminium industry bases its allocation on an economic aspect, such as the price elasticity for primary and secondary aluminium. Frees (2008) found that some 60–70 % of the demand for aluminium is made from primary source, and the avoided production by recycling will hence mainly be of primary aluminium. This 'scrap' deficit is similarly seen by the asphalt industry in Europe, where available reclaimed asphalt makes in general less than 35 % of a country's annual production (EAPA 2009).

$$\text{LCI of steel production} = \text{LCI}_{\text{pr}} - R \times Y \times \left(\text{LCI}_{\text{pr}} - \text{LCI}_{\text{re}}\right) \tag{1a}$$

Where:[1]

- R = recycling rate of the steel product;
- Y = process yield of the EAF (i.e. >1 kg scrap is required to produce 1 kg steel);
- LCI_{pr} = cradle-to-gate Life Cycle Inventory (LCI) for 100 % primary metal production. This is a theoretical value for steel made in the BF/BOF, assuming 0 % scrap input;
- LCI_{re} = cradle-to-gate LCI for metal production from 100 % scrap in the EAF;

[1] EAF: electric arc furnace; BF: blast furnace; BOF: basic oxygen furnace.

Equation 1a is equivalent to the 'approximation' method prescribed by PAS 2050 (Annex D), as shown by Eq. 1b ($R_2 = R$, $E_V = LCI_{pr}$, $E_R = LCI_{re}$) except that: (1) 'Y' is equal to 1 in PAS 2050 and (2) PAS 2050 includes the emissions of disposing of the material unable to be recycled. This rate $(1-R_2)$ is considered to be low (e.g. <15 %, rebar) or very low (e.g. <1 %, hot-dip galvanised coil) by the steel industry (World Steel Association 2008).

$$\text{Emissions/unit} = (1 - R_2) \times E_V + R_2 \times E_R + (1 - R_2) \times E_D \quad (1b)$$

Where:

- R_1 = proportion of recycled material input;
- R_2 = proportion of material in the product that is recycled at end of life;
- E_R = emissions arising from recycled material input, per unit of material;
- E_V = emissions arising from virgin material input, per unit of material;
- E_D = emissions arising from disposal of waste material, per unit of material;

It is noted, however, that unlike steel or aluminium, most bound pavement materials do not maintain the same inherent properties when recycled. LCA of road pavements thus tend to take the 'cutoff' method: each product is assigned only the burdens directly associated with it; in other words, all benefits of recycling are given downstream to using the recycled material, with no indication of the actual rate of, or potential for, recycling. This approach is also known as the 'recycled content' method (Hammond and Jones 2010), prescribed by PAS 2050 as in Eq. 2 with parameters denoted the same as in Eq. 1b.

$$\text{Emissions/unit} = (1 - R_1) \times E_V + (R_1 \times E_R) + (1 - R_2) \times E_D \quad (2)$$

LCA development has proposed an array of allocation methods; they were firstly stated by Ekvall and Tillman (1997) and evolved by Nicholson et al. (2009) into five main categories including the 'cutoff' and 'substitution' described above, and three other routes with their rationale listed below. Frischknecht (2010) indicated that the 'cutoff' method presents lower uncertainty associated with EOL use, and so may be endorsed by highway authorities, whilst the 'avoided burden' (equivalent to 'substitution') method prefers a short-term perspective that is likely to be supported by material manufacturers because there is an immediate benefit.

- 50/50 method: supply and demand are both necessary to enable recycling. Half the benefits of recycling are hence allocated to using recycled material, and the other half to producing the recyclable material.
- Closed-loop method: assumes that each product is equally responsible for the burdens associated with the entire product life cycle. The impacts are thus apportioned equally among products in the life cycle by the number of times recycling occurs.
- Loss of quality method: similar to the 'closed loop' method except that each product is assigned the burdens based on its value in the product life cycle (weighting factor). The rationale is that each time recycling occurs, the material suffers a loss in quality which necessitates a certain level of upgrading to restore its function. Material pricing data are commonly used as a proxy for quality.

asPECT takes the 50:50 route except changing the ratio to 60:40 (Wayman et al. 2011). The 'closed loop' and 'loss of quality' methods require knowledge of the fate of the material that is usually beyond the analysis period of a road pavement LCA, and thus have not seen any use to date. Case study 2, Section 5, compares EOL allocation of recycled asphalt using 'cutoff' and 'substitution' methods.

4 Case study 1

To test the sensitivity of road pavement LCA results to the allocation methods for co-products, a case study of a typical UK rural road is presented, in which different allocation rules for bitumen (conventional asphalt binder) and BFS (a 'waste' from iron production) are tested.

4.1 Project background and modelling[2]

The site is located East of Sutton Bridge, Lincolnshire on the A17, an interurban road in the UK Midlands. The length is 720 m on the approach to Norfolk, including 200 m length of dual carriageway (typical width, 22 m) at the County boundary, and 520 m length of single carriageway (typical width, 11 m). The 2009 traffic comprised of 430 OGV1+PSV and 820 OGV2 per lane per day. The site was fully reconstructed in 2009 with all asphalt layers removed and replaced with new, i.e. 200 mm DBM base, binder course and HRA surface course. All asphalt layers use BFS as coarse aggregates (>2 mm). This case study was chosen partly because it represents an extreme yet realistic case for the sensitivity of results to BFS allocation.

The construction data were provided by Lincolnshire County Council and are based on the UK asphalt material specification in compliance with BS EN 13108 (BSI 2010).

[2] OGV: other goods vehicle (OGV1: 2/3-axle rigid, OGV2: all other OGVs); PSV: public service vehicle; DBM: dense bitumen macadam; HRA: hot rolled asphalt.

The case study includes a cradle-to-laid reconstruction (inlay) in 2009. The inlay involved planing 200 mm of the old pavement out and replacing with new asphalt mixtures. All removed materials were stockpiled for reuse. The modelling is done in SimaPro software, with system boundary illustrated by Fig. 1. Allocation for BFS has followed both the 'mass' and 'economic value' route of the iron-making process, using iron/BFS ratio of 1 t:92.8 kg (Classen et al. 2009) and £333/t:£7.74/t (Metal Bulletin 2011; Langdon 2008). asPECT's zero allocation route has also been used. Eurobitume 2011 inventory data, based on mass, economic value and a mixed allocation described in Section 3.1, are used for bitumen. Only one material (bitumen or BFS) allocation was changed at a time.

4.2 Results and analysis

The variation in characterised results for the cradle-to-laid inlay process, by Eco-indicator (impact assessment method in SimaPro), due to change of allocation methods for bitumen (left) and BFS (right), is shown in Fig. 2. Results are shown relative to the mass allocation as a baseline equal to 100 %. In both bitumen and BFS cases, mass allocation leads to the highest characterised results in all impact categories. This type of result is believed to apply to many other construction materials because they tend to be bulky and of relatively low market price, compared to their co-products.

For bitumen comparison, the BFS is allocated zero impacts at point of production, consistent with asPECT. The change from Eurobitume (mixed) allocation to economic value allocation makes a difference of typically less than 15 % to the results of the whole case study. The impact of 'fossil fuels' shows the largest variation where economic value allocation leads to result 57 % of that of mixed allocation. This is believed to be caused by the low 'crude oil' input to bitumen production defined by Eurobitume's economic value allocation (Eurobitume 2011), and that the inventory of bitumen production contributes substantially more to the 'fossil fuel' than to other impact categories (e.g. 'climate change'). The change from mixed to mass allocation leads to little variation (less than 8 %). Due to there being only a cutdown LCI available for the different allocation types (Eurobitume 2011), for four of the impact categories, i.e. 'minerals', 'land use', 'ecotoxicity', and 'carcinogens', results do not change with the allocation method.

For BFS comparison, the bitumen allocation follows the Eurobitume (mixed) method, consistent with asPECT. Results of the whole case study vary significantly in all but one ('radiation') impact category, depending on allocation method for BFS. The change from mass allocation to considering zero impacts reduces the 'minerals' and 'carcinogen' impacts by more than 80 %. Even the change from economic value allocation to zero impacts causes a decrease of 50 % for 'minerals' and 'carcinogen'. This is believed to be caused by the inventory of iron production contributing greatly to these two impact categories. There is less variation (<20 %) between economic value and zero impacts allocation in other impact categories, yet both methods lead to results being significantly lower than mass allocation. This is due to the high percentage of BFS (35 % surface course and 70 % binder course/base) in the asphalt mix design (BSI 2010).

5 Case study 2

To test the sensitivity of LCA results to the 'cutoff' and 'substitution' methods for EOL recycling, a hypothetical asphalt mixture was designed, following UK material specification PD 6691 (BSI 2010). The functional unit is defined as 1 t of asphalt from cradle-to-gate. No recycled materials from other industries are included for this analysis. Parameters in Eq. 1b (substitution) and Eq. 2 (cutoff) are defined as below:

- R_1: recycled asphalt pavement (RAP) content, 30 % is used;
- R_2: asphalt recovery rate at EOL, 90 % is used;
- E_V: asphalt production (7.4 kWh electricity+8.3 l gas oil) per tonne, all virgin materials;
- E_R: breaking up existing pavement (1.9 l diesel) and RAP processing (0.3 l diesel), per tonne;

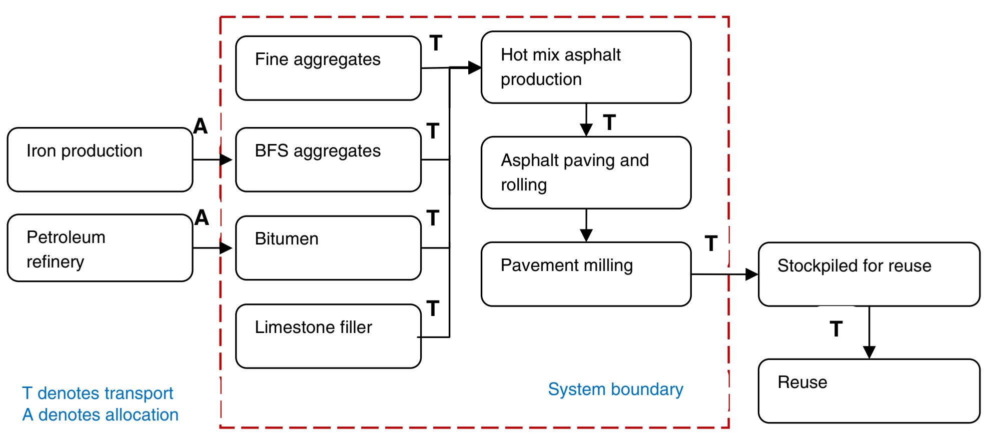


Fig. 1 System boundary of case study 1

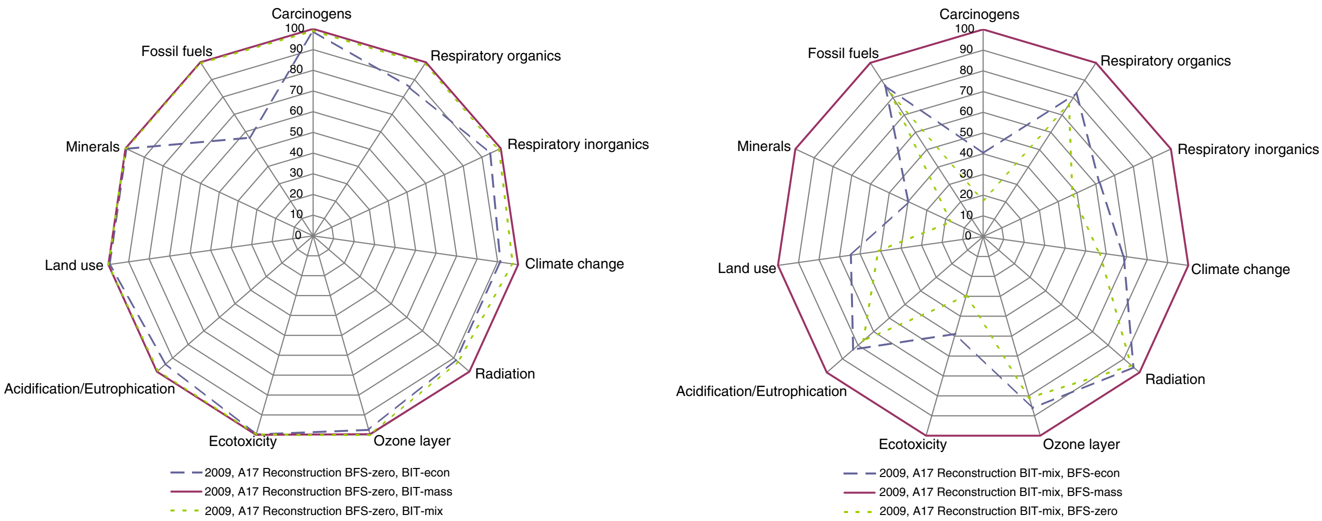


Fig. 2 Variation in total impacts due to bitumen (*left*) and blast furnace slag (BFS, *right*) allocation method

- E_D: transport to stockpile/recycling hub (landfill of asphalt is a rare practice in the UK);

SimaPro is used to model this simple case study, in which RAP replaces some of the constituent aggregates and binder, while the energy inputs to drying and heating are assumed to be the same. This approach is also used by asPECT; the rationale is that the introduction of RAP does not alter the manufacturing process, unless it results in a different mixture type (e.g. warm mix). Data on energy consumption of asphalt production are obtained from a major contractor in the UK based on plant average (Huang 2007). Data on pavement excavation and RAP production are obtained from a recent European research (ECRPD 2010). Transport is assumed to use 28 t truck, 50 km for quarry aggregates/RAP and 200 km for bitumen. Results are shown in Table 1 and Fig. 3.

Interestingly, the benefits of recycling (reduced characterisation results comparing to 'no recycling') vary across the impact categories, from 4 % (acidification) to 24 % (ozone depletion) for 'cutoff', and 8 % (acidification) to 70 % (ozone depletion) for 'substitution'. CO_2 figures per tonne asphalt production (cradle-to-gate) from the inventory are 62 kg (baseline), 59 kg (5 % less) and 53 kg (14 % less) for 'no recycling', 'cutoff' and 'substitution', respectively. The 'climate change' result in Table 1 and Fig. 3 show that the difference is 9 % (cutoff) and 26 % (substitution) instead, indicating the importance of measuring non-CO_2 GHG emissions from asphalt manufacture. The 'cutoff' and 'substitution' methods present two extremes of allocating the benefits of EOL recycling to material production. Any arbitrary choice between these two extremes, e.g. the 50:50 or 60:40 (as in asPECT) will lead to results falling between this range.

This case study includes some simplifying assumptions, in that no account is made for different drying requirements for RAP compared to virgin aggregate, or for any addition of chemical rejuvenator. Primary bitumen input was reduced assuming the binder in the RAP was fully recovered. In practice, the reduction in primary bitumen use associated with RAP will vary on a mixture-to-mixture basis. Including these considerations is likely to reduce the difference illustrated by this hypothetical model.

6 Conclusions and recommendations

There are many methodological questions concerning LCA of road pavements. UK PAS 2050 for measuring carbon footprints includes a methodology that needs to be tailored to address the specifics of pavement construction and use. asPECT was developed to provide consistency in boundary setting and allocation method for the UK road industry. Allocation to pavement materials and co-products should follow rules suitable for the process and fate of the materials involved. Some examples for bitumen and cement substitutes have been presented. To allocate the benefits/burdens of recycling at EOL to production/reuse, additional factors such as supply and demand that may determine the disposal scenarios (e.g. for aluminium) should be considered. The route taken by the steel industry is discussed in relation to the methods advised by PAS 2050.

Case study 1 indicated that the impact of BFS in general varies more than that of bitumen, to allocation methods, and it leads to a much larger change in the whole case study results. This can be attributed to the difference in material quantity, and that the bitumen/BFS inventory contributes more significantly to some impact areas than others. Mass allocation is found to consistently lead to the highest figures in all impact categories, which is typical of construction materials sourced as co-products from other industries. The change to economic allocation leads to a decrease of impacts from Eurobitume

Table 1 Inputs and outputs of case study 2

		1 t Asphalt (cutoff)	1 t Asphalt (no recycling)	1 t Asphalt (substitution)
Raw material inputs	Unit			
Quarry aggregates	kg	672	960	96
RAP	kg	300	0	4
Bitumen	kg	28	40	900
Impact category outputs	Unit			
Carcinogens	DALY	5.30E-09	5.84E-09	4.22E-09
Respiratory organics	DALY	9.23E-11	1.13E-10	5.23E-11
Respiratory inorganics	DALY	6.32E-08	6.88E-08	5.31E-08
Climate change	DALY	1.44E-08	1.58E-08	1.16E-08
Radiation	DALY	1.48E-10	1.79E-10	8.27E-11
Ozone layer	DALY	2.06E-11	2.69E-11	7.99E-12
Ecotoxicity	PAF × m^2 year	2.33E-02	2.75E-02	2.61E-02
Acidification/eutrophication	PAF × m^2 year	1.81E-03	1.97E-03	1.89E-03
Land use	PAF × m^2 year	6.36E-04	1.87E-03	1.46E-03
Minerals	MJ surplus	2.63E-04	4.17E-04	3.66E-04
Fossil fuels	MJ surplus	7.75E-02	2.24E-01	1.75E-01

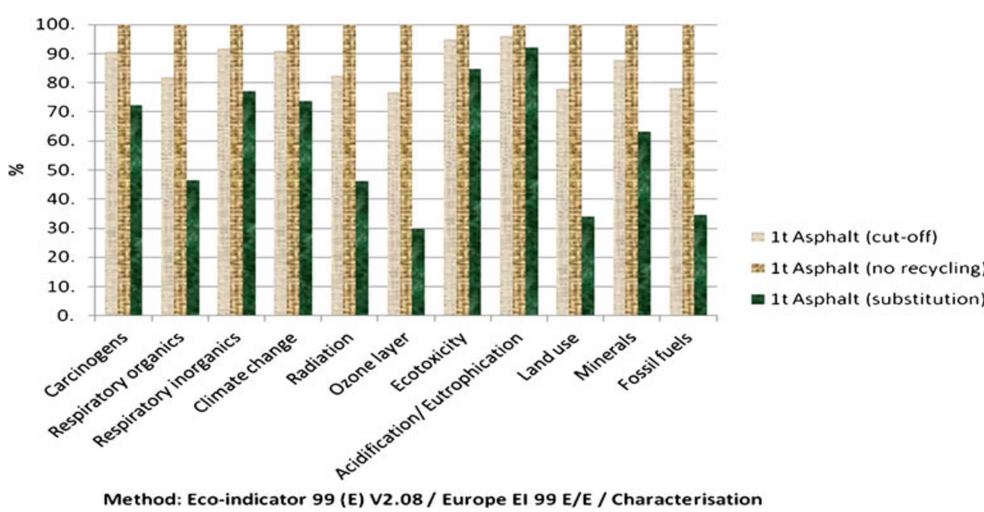
DALY disability adjusted life years; *PAF* potentially affected fraction

mixed allocation (see Fig. 2 left) and an increase of impacts compared to asPECT zero impact allocation (see Fig. 2 right). This can be attributed to the default allocation methods.

Generally speaking, pavement materials are dense and of relatively low value, so mass allocation to materials which are co/by-products of other sectors may be inappropriate. The high environmental impact values resulting from mass allocation may discourage the use of secondary materials, an area where the road industry has made significant progress. Allocation based entirely on economic value, on the other hand, is sensitive to variable geographic and temporal market factors. While zero allocation of 'waste' co-products (e.g. BFS) may encourage their use, it gives no benefits to the manufacturer of the primary material (e.g. iron), and raises the question of which co-products should be defined as 'waste'. Where it is impractical to avoid allocation by dividing the unit processes, economic allocation appears to be more appropriate than mass allocation for secondary pavement materials. However, for complex industrial processes with many product streams, different allocation methods may be appropriate for different stages of the product life cycle, such as in the Eurobitume example.

Case study 2 illustrated a simple model showing how the use of different allocation methods for EOL recycling affects the unit inventory results of asphalt production. Parameters in Eqs. 1b and 2 are likely to vary in each pavement project. Where the inherent properties of a material are not preserved, the cutoff allocation for EOL recycling may

Fig. 3 Variation for 1-t asphalt production due to allocation to EOL recycling



be most appropriate. A substitution method gives credits to the producer of recyclable material; this is however limited by the extent to which the final amount and type of recycling can be predicted, e.g. pavement materials with long lifetimes and multiple methods of recycling. Production of recyclable pavement materials continues to be important, so allocation by substitution may remain the best method, even though it may not be possible to fully justify the accurate division of credits between the producer and user.

Sensitivity analysis helps to understand the impact of the methodological choices on the LCA results. Case studies in this paper give some examples of how much the road pavement LCA results can change based on the choice of allocation method. Some design and construction options can also be modelled in LCA to test sensitivity. For instance, the use of surface dressing/thin surfacing overlay to reduce/delay the more resource-demanding reconstruction, and the traffic management options in the course of road maintenance. Some of these elements have been shown potentially to have a significant effect on the overall environmental impacts of pavements (Santero et al. 2011b). To answer these questions fully is likely to steer a pavement LCA in a project-specific direction, meaning that data and conclusions may not be transferrable. As a result, different functional units may need to be defined in the LCA model, to deal with different construction, condition, climate, location and traffic. The results of these studies can then be used in generating sector-specific rules (including the use phase) that are required as a step towards comparability and transparency in road pavement LCA.

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